DEVELOPMENT OF A WATERJET BARRIER FOR OIL SPILL CONTAINMENT

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ABSTRACT

A high pressure waterjet barrier is a concept that has shown promise as a means for oil spill containment in cases where a high water current is present, such as in rivers or tidal estuaries. A number of projects have been conducted over the past decade to develop a system of this type for field use. As the barrier's performance has been limited significantly by its flotation system during past deployments, recent work has been directed toward an improved low drag flotation system. This work included a review of the past performance of the barrier and a redesign of the barrier's general arrangement and flotation system. Towing tank tests were performed using full scale models of two alternative float designs. The current-induced drag of these floats was significantly reduced, to 30% and 60% of the original disc floats. A prototype system with boom arms 12m (40 ft.) long was constructed and a preliminary deployment took place in the St. Lawrence River at Prescott, Ontario during August 1991. A comprehensive series of deployments has been planned for the summer of 1992 at the same location.

BACKGROUND AND OBJECTIVES

Currently available oil containment booms are unable to function effectively at sites where the water current exceeds about 0.5 m/s (1 knot) and/or the wave conditions exceed about Sea State 3. There is a need to contain oil spilled in higher currents and sea states such as may occur in rivers and harbours. In recognition of this need a series of projects have been sponsored by Environment Canada and the U.S. Minerals Management Service (MMS) to develop a high pressure waterjet barrier for oil spill containment. Laboratory tank tests (Meikle,1983; Meikle et al.,1985; Hebron,1985; Phillips et al.,1987; and Laperriere et al,1987) and trial field deployments (Laperriere,1985; Punt,1990) have been conducted. These tests have shown that the waterjet barrier has promise as a means for oil spill containment in high current or more severe wave situations.

However during past deployments the performance of the waterjet barrier has been limited by the effectiveness of its flotation system. As a result, Fleet Technology Limited (FTL) was contracted by Environment Canada and the U.S. Minerals Management Service to redesign the flotation system and to produce a prototype for testing (Comfort and Paterson, 1991). The objective of this work was to produce a flotation system that would improve the manoeuvrability, directional control, and the stability of the waterjet barrier in the presence of high velocity water current.

REVIEW OF EXISTING SYSTEM AND PROBLEMS DURING PAST DEPLOYMENTS

Conceptually, the waterjet barrier consists of a large capacity, high-pressure pump connected to a series of nozzles that are elevated above the water surface and which are arranged to produce a horizontal spray pattern that opposes the spread of the oil on the water surface.

The "original" (ie. pre-1991) system used flexible hydraulic hoses to feed water to the nozzles; disc-shaped floats supported the nozzles and the hoses. There was no rigid structure joining individual floats or nozzles. The waterjet barrier has been deployed in two general configurations:

a) in two arms as a "Vee", which confines the oil at the apex of the "Vee" (see **Figure 1** and **Plate 1**); and:

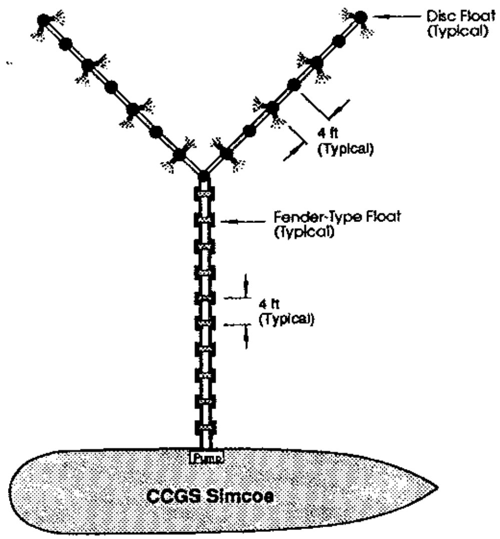


Figure 1: Waterjet Barrier Configuration Tested at Prescott, Ontario (By Punt, 1990)

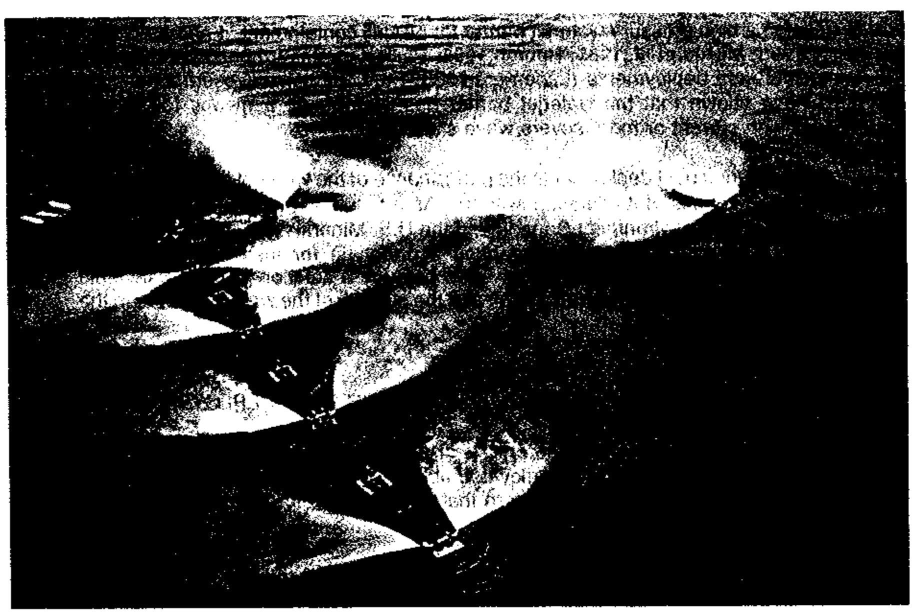


Plate 1: Waterjet Barrier During 1990 Trials at Prescott, Ontario

b) in a single arm, which is intended for applications where the oil is to be diverted (such as to a cleanup site on shore for an oil spill on a river).

For each operating configuration, the nozzles are located on 2.4 m (8 ft.) centres and are arranged such that opposing horizontal jets are produced. This general arrangement allows the arms of the barrier (for the "Vee" configuration) or the whole barrier (for the "diversionary" mode) to be manoeuvred using differential water pressure, controlled from a central manifold off of the high pressure pump. It also acts to stabilize the system while operating.

The most recent deployment of this "original" system was conducted in 1990 at Prescott, Ontario (Punt,1990). A number of problems were experienced at that time. The disc floats had excessive drag such that in a current of 0.5 to 0.75 m/s (1 - 1.5 knots) the barrier could not be manoeuvred and kept on station in the desired configuration (ie. with the desired angle between the arms of the barrier). The arms were also found to be too flexible, with the result that the system was difficult to control. Stability problems occurred as the disc floats overturned in some cases (see Plate 1). Also the height of the nozzles above the water in the original system was less than that identified for optimal oil retention performance (by Phillips et al,1987) in laboratory tests.

REVISED DESIGN: CONCEPT DESCRIPTION

Several approaches were considered for improving the waterjet barrier design. The alternatives fell into two general categories,as follows:

a) flotation system improvements, and:
b) general arrangement improvements.

A combination of both was utilized, as illustrated in **Figure 2**.

The **flotation system** revisions consisted of:

1.) use of an "airfoil-type" float that was able to "weathervane" in the current.
2.) a reduction of the number of floats by spacing them at 2.4 m (8 ft.) centres, rather than at 1.2 m (4 ft.) centres as in the "original" design.

The **general arrangement** of the system was also changed. To reduce the flexibility of the waterjet barrier and reduce the number of floats required, it was decided to support the hydraulic hoses rigidly with aluminum square tube sections between the floats. Each support is pinned together to allow movements in the vertical direction.

Past experience had shown that it is desirable to allow the angle of the arms at the apex to vary for improved oil retention performance. To achieve this, the arms of the barrier were pinned vertically at the apex structure.

It was recognized that the revised design was more complex than the "original" barrier. These revisions were considered necessary in order to resolve the problems experienced with the original system during previous deployments.

DESIGN OF THE WATERJET BARRIER FLOATS

<u>Objectives of the Float Design</u>

The new floats were designed to meet three main performance objectives:

1.) **Support the weight of the barrier and maintain a nozzle elevation of approximately 20cm (8") above the waterline.**
2.) **Improve the stability of the barrier under the action of the water jets.**
3.) **Reduce the drag of the floats in current up to about <u>2 knots</u> (1 m/s).**

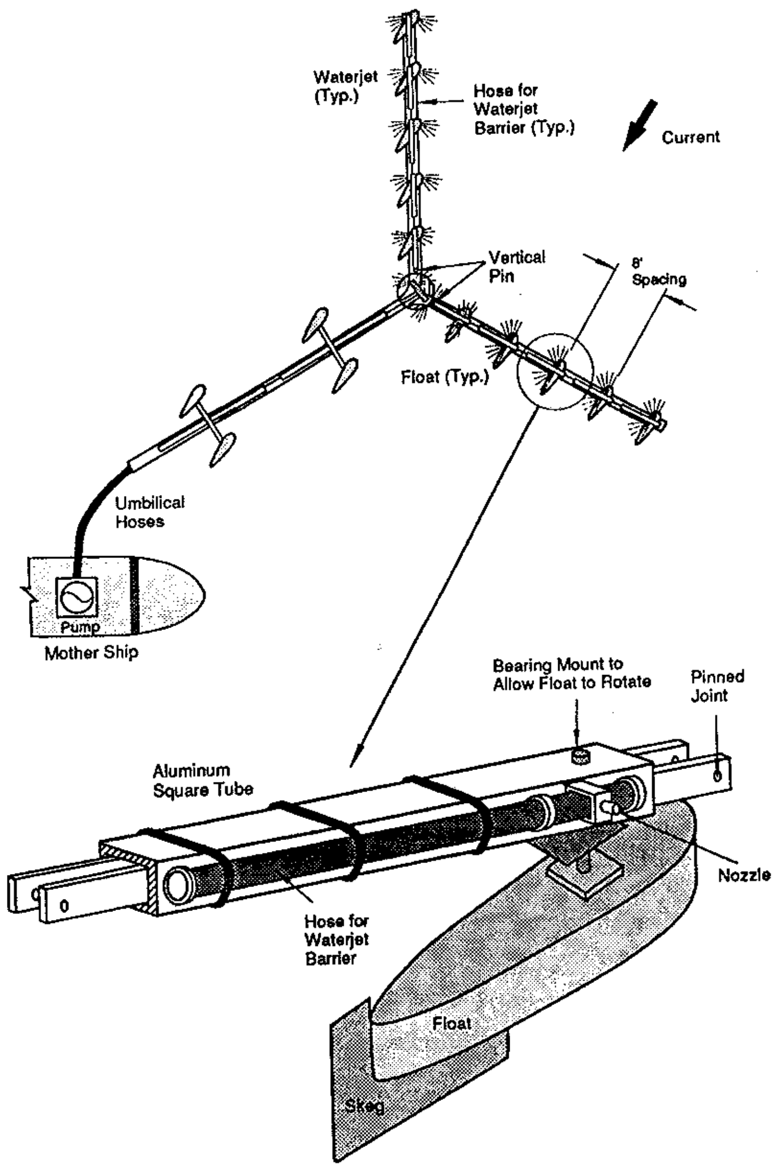


Figure 2: General Arrangement of Revised Waterjet Barrier

The actual float configuration was driven by objective "3", reduction of the float drag, although achievement of the first two objectives were necessary for any successful float design. The review of past designs indicated strongly that drag reduction was critical for providing acceptable station-keeping performance and controllability of the waterjet barrier.

Selection of the Float Hull Form

A number of float concepts were generated, including the possibility of retaining a circular float form. The design effort quickly focused on the "airfoil" type float as the form offering the greatest potential drag reduction, and favourable motion characteristics in waves. However the selection of an airfoil form introduced the requirement that the float must "weathervane" to maintain a favourable (ie. low drag) heading into the current. Two variations of the airfoil float were evaluated for use on the boom arms, as shown in **Figure 3**.

Concept LF1: the Short Airfoil or the "Airfoil Strut" float.

The basic sectional shape was conceived as a section with an elliptical nose and parabolic tail, offering the best potential weathervaning response. A "standard" airfoil section, with a length of 1m, an L/B ratio of 4, and the maximum breadth at 30% of the length, forward was designed from Hoerner (1965). The concept was developed as a strut ie. greater depth to length, in order that heave (vertical translation) would be the dominant motion response in waves.

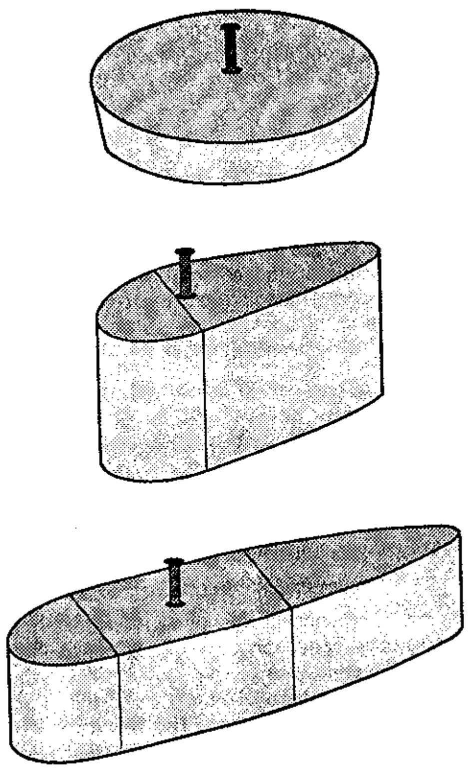
The major penalty associated with the "strut" concept was its short length, which would result in a higher speed:length ratio at the upper speed range. It was unclear whether the superior form drag of the float would offset the resistance penalty associated with the wave system developed at a high speed:length ratio. An additional penalty was that the float would be highly laterally unstable due to the low centre of buoyancy. This was a concern during boom deployment and because of the potentially large moment that would be placed on the float pivot bearings.

Concept LF2: the Long Airfoil or the "Boat Hull" float

This variant was longer with a much shallower draft than the SF1 concept. Producibility and durability concerns precluded more complex hull shapes and finer hull sections, while the weathervaning requirement introduced a length limit. Standard ship hull form ratios provided guidance with regard to L/B ratio and the relative influence of other hull parameters. To obtain similar motion responses to the short airfoil concept, the beam was restricted to the same range (0.2 -0.3m). This resulted in a slender, deep, hull form. A standard "slender" form based on an L/B ratio of 6.5, with the nose and tail section of airfoil SF1 and the length constrained to 1.625m to avoid interference between adjacent floats during rotation.

The main attribute of this concept was its increased length, which meant a lower wave making drag. In addition, the concept features a large waterplane area, which allows for weight changes in the structure above, while still featuring a relatively slender hull form, necessary for "platforming" (cutting) through waves. There was a concern that the length constraint produced a float where the extremities are quite "full", ie. have "U" sections and large waterplane area at each end, and therefore may be prone to "pitch" in waves, despite a relatively high L/B ratio.

The main concern with the long airfoil concept was its ability to weathervane; the additional length placed the nose section well forward of the pivot while the parallel midbody resulted in a greater fore-aft symmetry; it was expected that a skeg (fin) would have to be

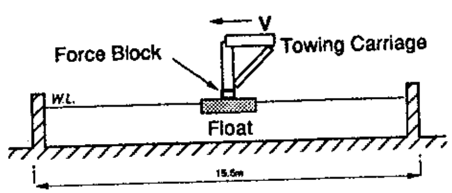


Disc Float
– from "Original" Barrier
Diameter = 1 m
Depth = 0.15 m

Float SF1
L = 1 m
B = 0.25 m
L/B = 4
Max. Chord = 0.3 from nose
Depth = 0.5 m

Float LF2
L = 1.625 m
B = 0.25 m
L/B = 6.5
Mid Body Length =0.625
@ 0.3 from nose
Depth = 0.30 m

Figure 3: Alternative Float Concepts



Force Block Data

Force Block No:	9
Outside Dimensions:	10cm x 10cm x 10cm (4in x 4in x 4in)
Wall Thickness:	1.6mm (.0625in)
Capacity:	250 N (50 lbs)
Sensitivity:	7.0097 x 10^{-4} mv/V/N

Figure 4: Schematic of Towing Test Apparatus – FTL Towing Basin

TABLE 1:
Summary of Experimental Resistance Results for Waterjet Floats

	Model:	Disk	SF1		LF2	
V(knots)	V (m/s)	Mean Rm(N)	Mean Rm(N)	Calc. Rc (N)	Mean Rm(N)	Calc. Rc (N)
0.58	0.3	2.24	0.69	0.86	0.65	0.67
0.58	0.3	2.34	-		0.53	
0.97	0.5	6.38	2.09	2.11	1.08	1.66
0.97	0.5	6.38	1.92		1.04	
1.36	0.7	12.25	4.55	4.32	2.00	3.40
1.36	0.7	12.35	4.64		2.38	
1.55	0.8	-	6.80	-	3.73	-
1.55	0.8	-	7.14		3.35	
1.75	0.9	-	11.41	-	5.84	-
1.75	0.9	-	11.31		7.58	
1.94	1	25.25	15.12	7.20	9.16	5.70
1.94	1	25.45	15.14		8.16	

Note: Velocities are nominal based on Speed Control Setting

1.1 Measured Thrust Developed By Waterjet:	
1) At 500 psi: Thrust =	62.4 N
2) At 1000 psi: Thrust =	106.4 N

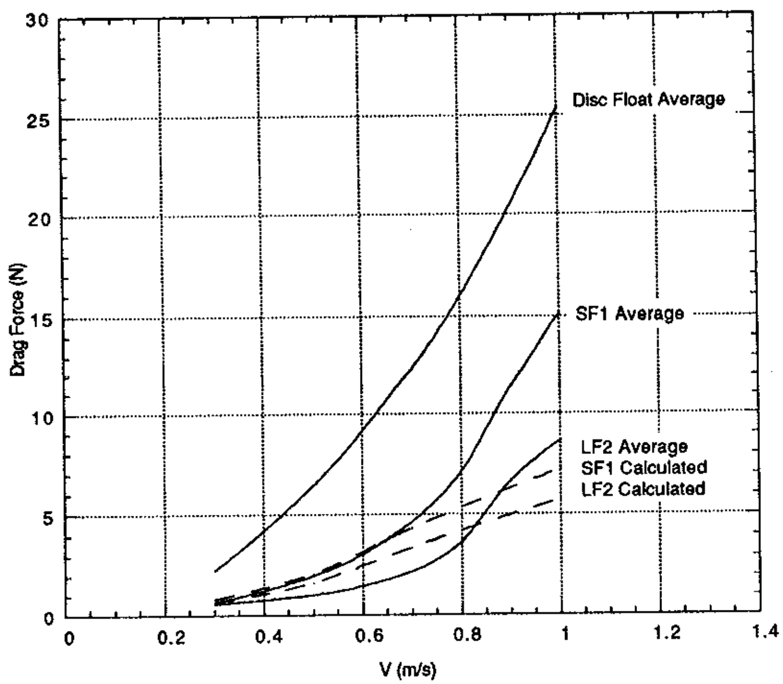
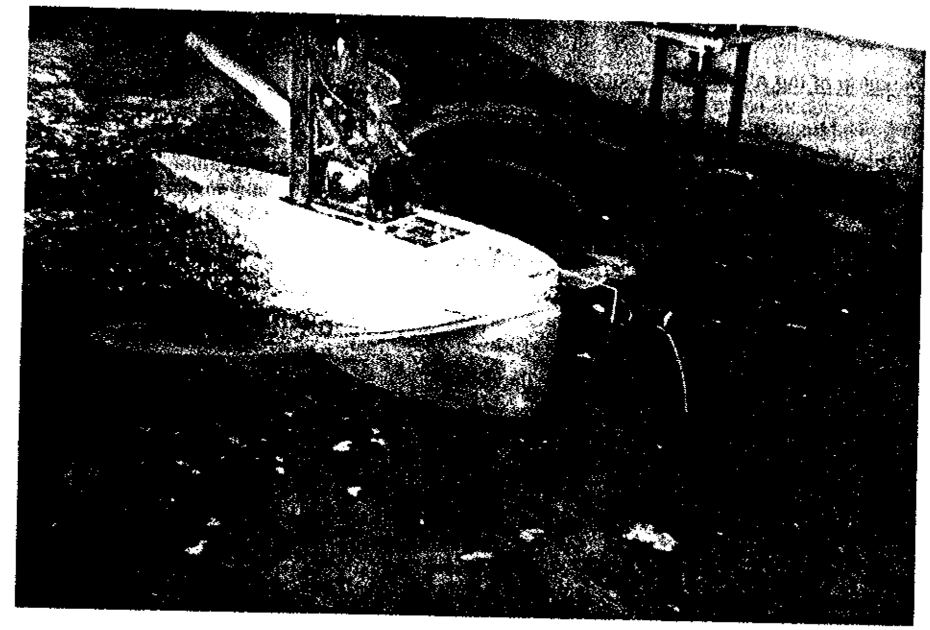
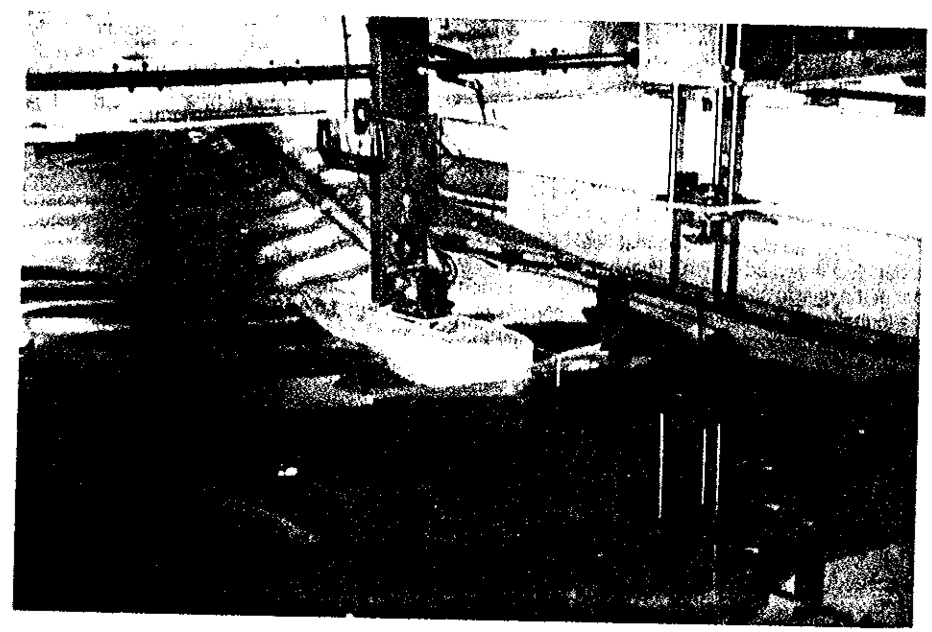


Figure 5: Measured Drag Versus Towing Speed



a) SF1



b) LF2

Plate 2: Comparison of Wave Systems at High Speed; SF1 and LF2

Evaluation of the Airfoil Float Concepts

The evaluation of the two float configurations was based on tests conducted in FTL's towing basin in Kanata using full scale prototypes. These trials had two phases:

1.) Resistance trials to measure the total drag on each of the prototypes; it was found that the long airfoil (LF2) had the lowest drag.

2.) Determine the weathervaning characteristics of the float with least resistance (LF2); development of an appropriate skeg.

Results of Resistance Trials

Resistance tests were performed on three different models:

1.) the disk float - used in the "original" flotation system, as a baseline for evaluation
2.) the airfoil float SF1
3.) the boat hull float LF2

Refer to Figure 3 for sketches and the dimensions of each float.

The trials were performed over a nominal speed range of 0.3 - 1.0 m/s (0.6 - 2 knots), with approximate increment of 0.25 m/s. At least two tests were performed at each speed, and additional tests were performed at smaller speed increments at the higher speeds where resistance (drag) increased dramatically. A schematic of the towing arrangements is shown in **Figure 4**. The mean measured resistances for each model are given in **Table 1** and plotted in **Figure 5**.

Numerical drag estimates were prepared for each of the candidate float and the original disk float, based on the empirical formulae found in Hoerner (1965) and Comstock [PNA] (1967). It should be noted that the numerical analysis did not contain an estimate for the wave-making drag component, as no simple formula was available for these forms. Consequently the accuracy of the drag estimates was expected to change dramatically as speed increased and the wave-making component became more significant. The numerical drag estimates are included in Table 1 and plotted in Figure 5.

The data clearly shows that float LF2 had the lowest drag of the floats tested. The model tests indicated that this float has approximately 30% of the drag of the baseline disk float at the design speed of 2 knots (1 m/s). The short airfoil float had a higher drag, largely due to the wave making resistance. This conclusion was supported by observations of the wave pattern associated with each float shown in **Plates 2a and 2b**, which show a significant wave system associated with the short airfoil float (LF2) at the design speed. Thus it was determined that the additional length of the long airfoil, which reduces the speed:length ratio (or Froude Number) and thereby the associated wave-making action, was the key factor in minimizing the float drag.

A separate set of tests were conducted to measure the reaction force exerted from a single waterjet nozzle. The object was to compare the force created by the nozzle with the hydrodynamic drag forces on the float. The results of these tests are also included in Table 1. The results suggested that there will be adequate nozzle thrust available to manoeuvre the barrier on correctly weathervaning floats.

Weathervaning Trials

The second part of the model trials involved testing the weathervaning capability of the LF2 float design, selected for development following the resistance trials. The model was fastened to the towing post through a roller bearing that allowed the model to freely rotate in yaw (ie., in the plane of the water surface). The model was towed from an initial angle to the direction of towing. The turning response of the model as it was being towed

was recorded on videotape. No force data was collected. The response of the model was judged on whether it aligned itself fully with the towing direction over the length of the trial.

The weathervaning trials were performed systematically over a range of initial orientations, consisting of 0, 45, 135, and 90 degrees to the towing direction. The model was towed at 0.5 m/s for most runs, followed by low speed tests at 0.3 m/s and a high speed test at 0.7 m/s.

The initial trial was performed without any skeg. These tests indicated that a skeg would be necessary to achieve the required weathervaning performance. A skeg is simply a flat vertical plate fitted to the stern of the float which would alter the pressure distribution along the float length without adding displacement.

After some experimentation, a skeg configuration using an "L" profile, with the foot of the "L", or keel, running forward under the float to the parallel midbody was selected. This configuration was selected because it offered the best increase in skeg area for the minimum increase in length and depth of the float. Restricting the depth of the float was desirable for deployment in shallow water, and for durability. The skeg arrangement is shown in **Figure 6** which shows the general arrangement of the float.

Initial Design of the Umbilical Floats

Along the umbilical structure connecting the waterjet boom arms to the pump there are four hoses (instead of two) so the supporting floats have to be correspondingly larger. There was additional displacement required for the float at the junction of the "Y", because of the weight of structure located at the apex. It was proposed to obtain the added buoyancy using the LF2 float waterplane section with additional depth, rather than an overall increase in dimensions. See Figure 6. The result was a deeper float which was much less stable than the boom arm floats but was very simple (and less costly) to construct, because a common mould could be used, as described below.

It was subsequently found in the initial deployments that the umbilical floats had an unacceptably high profile and poor stability, which could limit the mobility of the barrier. A revised umbilical flotation system was designed that is described below.

Fabrication of the Waterjet Barrier Floats

It was decided to employ conventional fibreglass boat building methods to efficiently produce the quantity of floats required for the complete waterjet barrier. This technique is suited to quantity production because a re-useable mould is used to produce the hull shell. In addition, this mould was designed with sufficient depth to manufacture both sizes of float, for the boom arms and the umbilical structure.

The hull shell is made of fibreglass formed over the mould, with a hard smooth, Gelcoat exterior. The shell is reinforced with 3/4" (1.9cm) plywood transverse frames and a full-length 3/4" plywood deck. The float skegs were fabricated in 3/16" (0.5cm) aluminum, and attached to the float hull through 2"x 2"x 1/4" (5cm x 5cm x 0.635cm) aluminum angle brackets. The edges of the keel plate angle were extensively rounded (faired) to minimize parasitic drag. The entire skeg assembly is designed to be removable in the event of damage to the skeg plate.

The floats are connected to the boom structure through a pivot post consisting of 1" (2.5cm) rod welded to a flat metal baseplate, which is secured to the float deck by four heavy screws.

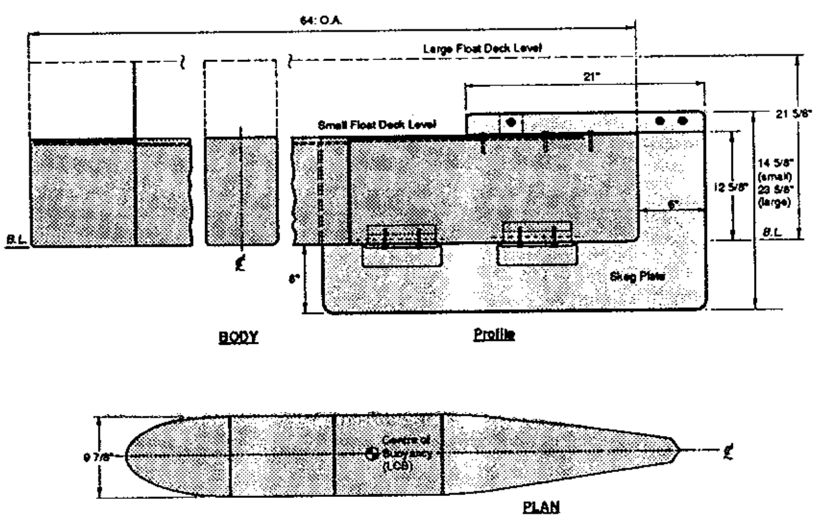


Figure 6: General Arrangement of Float

REVISIONS TO THE BOOM OUTFIT

It was expected that some constraint on the weathervaning action of the floats might be required, particularly during deployment and during low current conditions. Subsequent preliminary deployment trials, discussed below, verified this. Because the floats are slender, with weight of the boom arms well above their centres of buoyancy, the individual arm can capsize should the floats align too closely with the axis of the boom arm. Two types of float constraint are fitted, which allow the float to weathervane through an angle of about 90°:

1.) Stops fitted to each float, as shown in **Figure 7a**.
2.) Linking cables joining each float at the skeg, such that they weathervane in unison as shown in **Figure 7b**. A level of redundancy is also introduced should a stop fail.

A review of the deployment problems with the earlier boom designs suggested that the reliance on the waterjets to maintain position and control was excessive. It was recognized that deployment would be simplified by physically constraining the movement of the arms and of the boom position; the waterjet action would then be used for "local" control of the boom position and orientation. Thus two types of constraint are proposed, as shown in **Figure 8**:

a) Cables linking the individual boom arms; when fully extended the boom will be maintained at a specific limiting angle. The waterjet action will allow the operator to vary the boom opening angle from the limiting angle.
b) An anchor (or anchors) to maintain the basic position of the boom. The waterjets will allow the operator to move the boom around the anchor position.

PRELIMINARY DEPLOYMENT EXPERIENCE

A preliminary deployment of the revised waterjet barrier took place in late August of 1991 at the Coast Guard Base at Prescott, Ontario. Somewhat ironically, the weather during the trial period was generally characterised by high winds (+30 knots) and waves up to 1m. Because this was the first deployment of the revised boom, only a single deployment was attempted under these conditions, in the shelter of a small boat basin at the base. A photograph of the deployed boom is shown in **Plate 3**; note the boom was tethered from the ends of the boom arms.

The following conclusions were drawn from this deployment:

1.) It was demonstrated that the boom could be controlled under calm conditions by varying the waterjet pressures. The boom opening angle and the orientation of the boom could be varied using differential waterjet pressure controlled from the pump manifold.

2.) The revised flotation system was found to float at the design waterline such that the waterjet nozzles were placed at the appropriate elevation above the water surface. See Plate 3.

3.) Prior to activation of the waterjets, the boom was found to be affected by the high winds despite a relatively low profile above the water. In the absence of water current, the wind would tend align the floats with the barrier structure, such that the structure could capsize. The single umbilical floats, which had a higher above-water profile were most affected. This observation resulted in a couple of actions:

a) The single umbilical floats were replaced by a catamaran system of smaller floats, as shown in Figure 2. This revised arrangement should be more stable and will have a lower profile, but has not yet been tested.

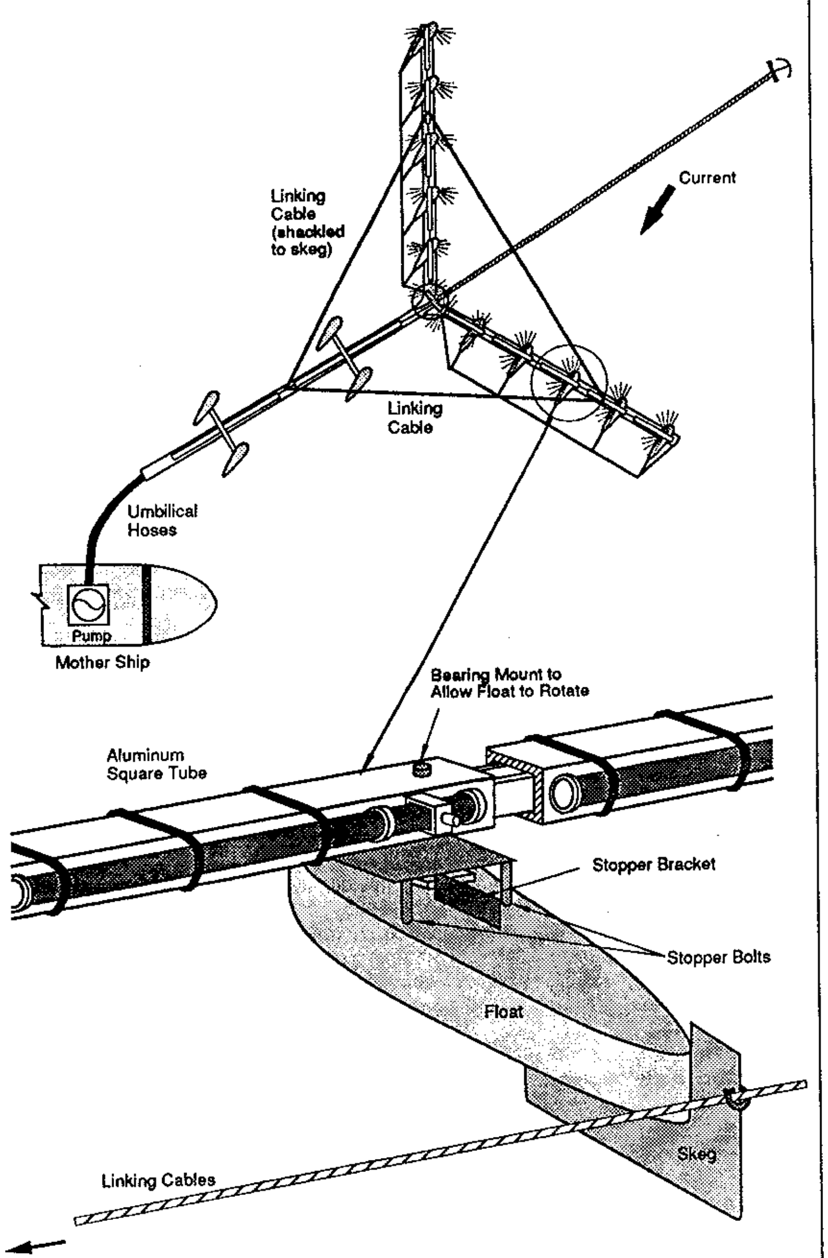


Figure 7: Constraints on Float Weathervaning Action

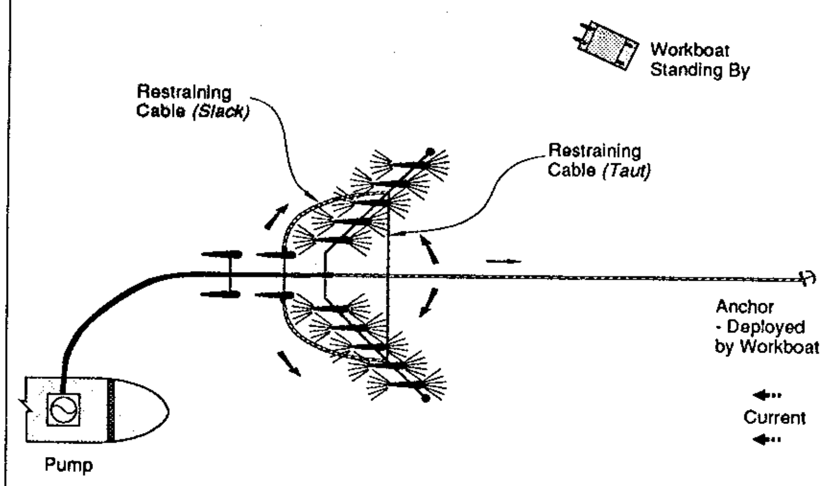
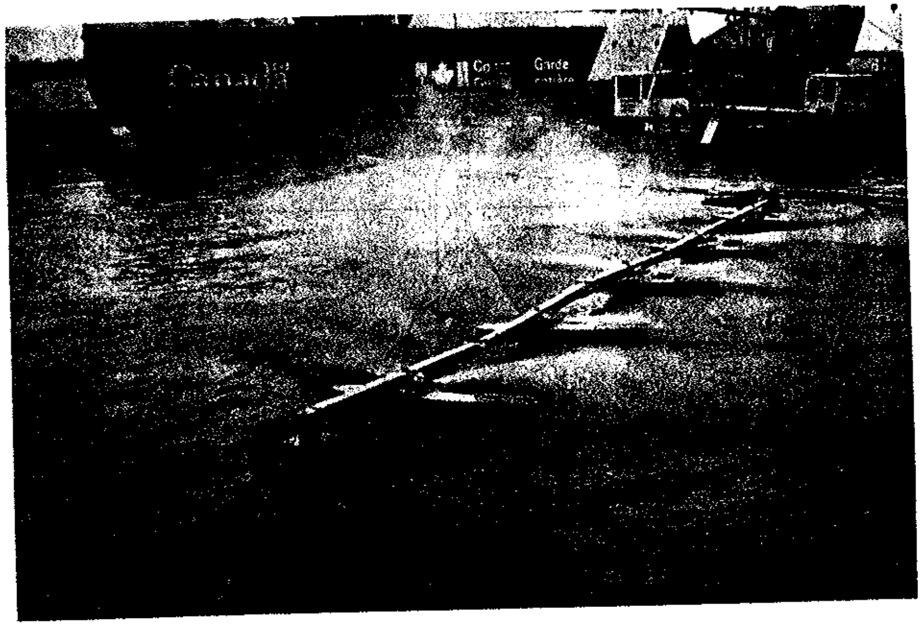


Figure 8: Proposed Boom Constraints



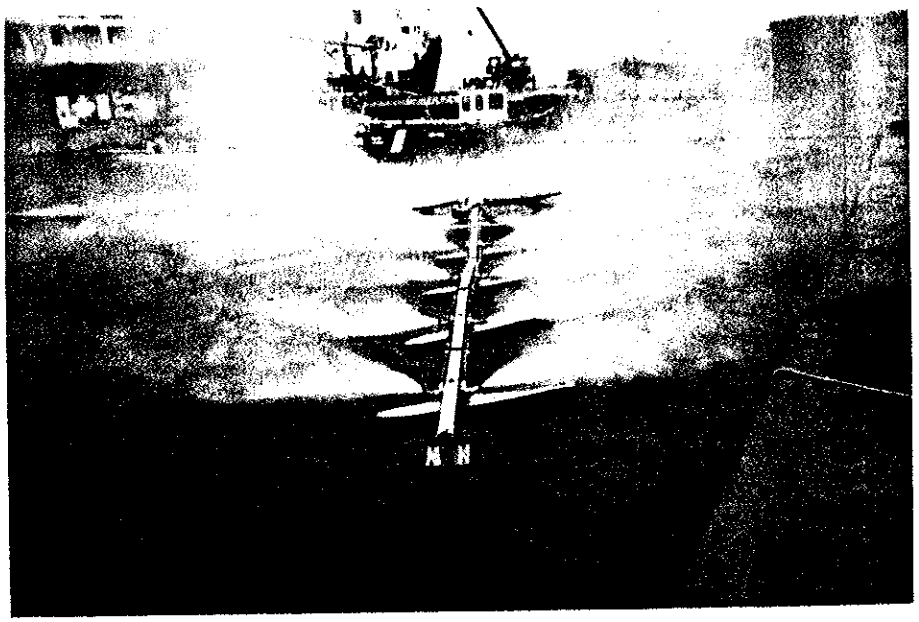


Plate 3: Deployment of Revised Boom in Small Craft Basin CCG, Prescott, August 1991

b) The weathervaning constraints consisting of the stops and the skeg linkages were found to be necessary to counter the wind, and in fact had to be reinforced during the deployment.

4.) The individual boom arms were exposed to waves estimated to be 0.3- 0.6m during the trials, and the wash from passing ships. The arms were observed to ride the waves and maintain a horizontal attitude.

5.) Revisions to the hose connection system would facilitate deployment. The current system uses pairs of threaded connections which require considerable effort to connect. However the current system will be retained for the proposed series of trials which are intended to demonstrate the waterjet barrier concept.

PLANNED FURTHER DEPLOYMENTS

Encouraged by the experience obtained during the preliminary deployment, a more comprehensive set of trials is planned for the summer of 1992. These trials will encompass a series of phased deployments under field conditions at CCG Prescott. The trials are intended to evaluate the controllability of the boom under the prevailing current and wave conditions from a shore location and in mid-river from a base vessel. The containment effectiveness will be assessed using canola oil to simulate an oil spill. Water pressures will be monitored from gauges fitted at the pump manifold. The results of these trials will be used to evaluate the overall effectiveness of the waterjet barrier concept and recommend improvements to the current waterjet barrier configuration.

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PROCEEDINGS OF THE FIFTEENTH ARCTIC AND MARINE OIL SPILL PROGRAM TECHNICAL SEMINAR

COMPTE RENDU: 15e COLLOQUE TECHNIQUE DU PROGRAMME DE LUTTE CONTRES LES DÉVERSEMENTS D'HYDROCARBURES EN MER ET DANS L'ARCTIQUE (AMOP)

JUNE 10-12, 1992
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